Journal of Ovonic Research Vol. 6, No. 4, July-August 2010, p. 181 – 185

GEOMETRICAL INFLUENCE ON PHOTONIC BANDGAP OF THREE DIMENSIONAL CHALCOGENIDE PHOTONIC CRYSTALS

B. SUTHAR*, A.K. NAGAR, A. BHARGAVA
Nanophysics Laboratory, Department of Physics, Govt. Dungar College, Bikaner-334001, Rajasthan, India

On the basis of Maxwell's equations and a plane wave expansion method, photonic band structure is computed for 3D chalcogenide photonic crystal with diamond lattice. The geometrical influence on the photonic bandgap is studied for three dimensional chalcogenide photonic crystal of diamond lattice for both chalcogenide spheres in air and air spheres in chalcogenide background. The air spheres in chalcogenide structure of 3D photonic structure has wide photonic bandgap in comparison to chalcogenide spheres in air.

(Received July 6, 2010; accepted July 30, 2010)

Keywords: 3D Photonic crystals, Photonic bandgap, chalcogenide, etc.

1. Introduction

In recent years, the researchers have been attracted a lot towards photonic crystals due to their control over light propagation [1, 2]. The reason to form a photonic band gap (PBG) is the inference of Bragg scattering in a periodic dielectric structure. This periodicity, whose length scale is proportional to the wavelength of light in the band gap, is the electromagnetic analogue of a crystalline atomic lattice, where the latter acts on the electron wave function to produce the familiar band gaps of solid-state physics [3, 4]. The calculation of band structure in these materials is important to investigate the properties for a particular system. The Plane Wave Expansion method (PWEM) is well known and has been used in this work. Photonic crystals possessing a PBG in the microwave, millimeter, and submillimeter ranges have been obtained in model systems [5, 6]. To study the properties of photonic crystals in the submicron region (visible light), colloidal systems consisting of polystyrene spheres undergoing self-ordering in a liquid dispersion medium are now being studied [7].

Mostly, Photonic Crystals have been made from III–V semiconductors. While their active functions have typically exploited thermal or free-carrier nonlinear effects, both of which are relatively slow [8]. Chalcogenides have generated great deal of interest due to their attractive properties [9]. Some of these are: can be formed over a large range of compositions; refractive index is high, linear absorption losses are low over a wide wavelength range and a large $\chi^{(3)}$ nonlinearity (much larger than Silica) [10]. Therefore, the chalcogenide glass photonic crystal platform appears to be a promising architecture for confining, guiding light and all-optical switching applications [11, 12].

In this paper, we have presented the results obtained for the 3D chalcogenide photonic crystal of diamond lattice structure of both chalcogenide spheres in air and air spheres in chalcogenide medium. The geometrical influence on photonic bandgap of the above structure will be studied. The size of the sphere as well as the refractive index contrast influence on the bandgap width of 3D chalcogenide photonic crystal of diamond lattices.

*Corresponding Author: bhuvneshwer@gmail.com

2. Theoretical Method

A straightforward way of solving for eigenvalues and eigenfunctions is to expand the dielectric constant as well as the periodic part of the Bloch function into a Fourier series on the reciprocal lattice, transforming equation into an eigenvalue problem for an infinite matrix which must be suitably truncated to become accessible to an approximate numerical solution. Owing to its simplicity and flexibility in handling practically any geometry of the unit cell, this so-called plane wave method (PWM) has become the work house for most investigations of photonic band structures [15].

Although there are an infinite number of geometries of 3D chalcogenide photonic crystal, we are especially interested in those geometries which exists the photonic bandgap. In our previous study of two dimension photonic crystal, we have seen that the less symmetric structure triangular lattice structure has complete bandgap in respect of highly symmetric square lattice structure [16]. Therefore, the diamond lattice structures promote the existence of photonic bangap in case of three dimensional crystal structure. As figure 1 presents the schematic diagram of 3D diamond lattice structure of spheres in unit cell.

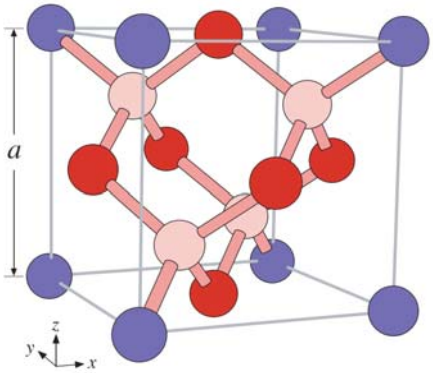

Fig. 1. The schematic diagram of 3D diamond lattice structure.

The photonic band structure for three dimensional chalcogenide photonic crystal of diamond lattice of As_2Se_3 in air is calculated using the plane wave expansion method, which is as shown in figure2. This band structure is plotted for only first Brillouin zone. Where X, U, L, Γ, K, W are the edges points of irreducible Brillouin zone. The radius of As_2Se_3 chalcogenide is $r = 0.22\ a$, where a is the lattice constant while the dielectric constant of As_2Se_3 chalcogenide is $\varepsilon = 8.02$. The number of plane waves are chosen to be N = 343 to optimize the value of photonic band structure.

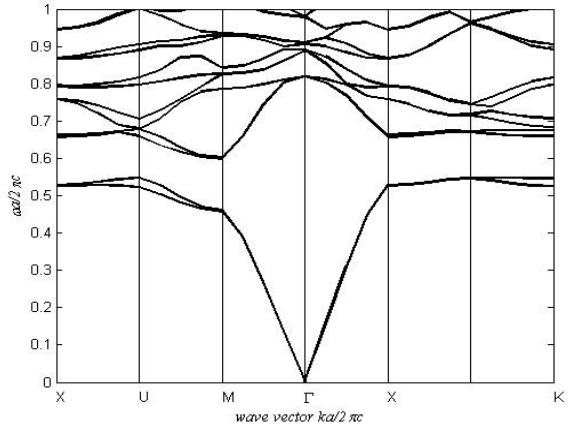

Fig. 2. The band structure for lowest bands of 3D chalcogenide photonic crystal with diamond lattice of As_2Se_3 spheres in air.

3. Results and discussions

The results of two dimensional photonic crystals have suggests that the lower symmetric structure is more useful than the highly symmetric structure for finding the complete bandgap [17]. The complete bandgap is present due to dielectric veins for TE polarization while due to dielectric spot for TM polarization. We have made a systematic examination of the photonic band structure for chalcogenide spheres in air as well as air spheres in chalcogenide on a diamond lattice as a function of refractive index contrasts and radius of spheres. A useful characterization of the photonic band, which is independent of the scale of the crystal, is gap to midgap ratio. Let ω_g be the frequency at the middle frequency of the gap and $\Delta\omega$ is the bandgap frequency; we define the gap to midgap ratio as $\Delta\omega/\omega_g$. The gap to mid gap ratio ($\Delta\omega/\omega_g$) as a function of radius of spheres is plotted in figure 3.

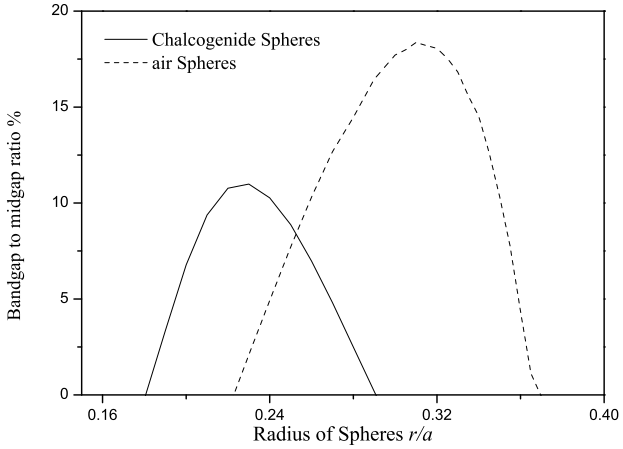

Fig. 3. The bandgap to midgap frequency ratio ($\Delta\omega/\omega_g$) as a function of the radius of spheres for the case of 3D chalcogenide photonic crystal with diamond lattice of As_2Se_3 spheres in air and air spheres in As_2Se_3 chalcogenide.

For As_2Se_3 chalcogenide spheres on a diamond lattice a maximum bandgap to midgap ratio ($\Delta\omega/\omega_g$) reaches upto 11%, is found at radius of chalcogenide spheres $r = 0.23a$, whereas for the case of air spheres in chalcogenide, $\Delta\omega/\omega_g$ can reach 18.36% at radius of air spheres $r = 0.31a$. It have noticed that in the diamond structure, all the bands along the symmetry line from W to X are required to have twofold degeneracy, which favours the opening up of a gap between the second and third bands. It also found that a band gap can be formed in the diamond structure at relatively low refractive index contrasts [1].

As the previous result shows that the photonic bands tend to appear in the photonic crystal with high index contrast [17]. The more significant scattering of light, the more likely a photonic bandgap will open up. For a given photonic structure, there is no photonic bandgap until the dielectric contrast is increased to some threshold value [15, 17]. Above this nonzero threshold value, the bandgap opens up and its width usually increases monotonically with dielectric contrast, assuming the optimal parameters are chosen. The optimal structure parameters (e.g. the radius of the spheres), which maximize the width of the photonic bandgap, varies with dielectric contrast of chalcogenide photonic structure.

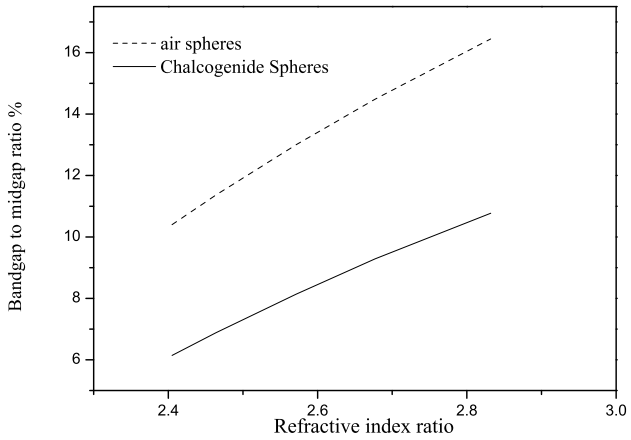

Fig. 4. The bandgap to midgap frequency ratio ($\Delta\omega/\omega_g$) as a function of refractive index contrast for the case of fixed structure 3D photonic crystal with diamond lattice of chalcogenide spheres in air and air spheres in chalcogenide.

We plot in figure 4 the bandgap to midgap ratio $\Delta\omega/\omega_g$ as a function of refractive index contrast for a fixed chalcogenide structure. The radius of spheres $r = 0.22\ a$ is kept constant for the case of chalcogenide spheres in air and $r = 0.29\ a$ kept constant for air spheres in chalcogenide background. For both cases a photonic bandgap exits from $As_{40}S_{60}$ to $As_{40}Se_{60}$. As we move from $As_{40}S_{60}$ to $As_{40}Se_{60}$ the Se-concentration continuously increases, which affect the refractive index value. The effect of Se concentration can be understood as follows. The value of the band gap in chalcogenide glasses is determined by the energy difference between the non-bonding valence band and the anti-bonding conduction band and not by the bond between the chalcogen and the arsenic atoms. The replacing sulfur atoms by selenium atoms decrease the value of the band gap from 2.1 eV for As_2S_3 down to 1.5 eV for As_2Se_3. The decrease in band gap causes increase in the values of nonlinearity which gives rise to the refractive indices from As_2S_3 for 2.405 to As_2Se_3 for 2.832 [18].

4. Conclusions

In conclusion, we have calculated the complete photonic bandgap for 3D chalcogenide photonic crystals of diamond lattice structure. This calculation scheme provides a very efficient way to obtain the crystal structure as well as the optimum parameters for maximizing of the photonic bandgap. The photonic bandgap is influenced with the geometrical parameters (i.e. the radius of the spheres as well as the refractive index) in both case of chalcogenide spheres and air spheres. The air spheres in chalcogenide structure are more powerful in sense of wide photonic bandgap applications.

Acknowledgement

One of us (B. Suthar) is thankful to CSIR, New Delhi for financial support in form of a fellowship.

References

[1] J.D. Joannopoulos, R.D. Meade, J.N. Winn, Photonic Crystals: Molding of Flow of Light, Princeton University Press, Princeton (1995).
[2] S. G. Johnson, J.D. Joannopoulos, Photonic Crystals: The Road From Theory to Practice, Kluwer Academic Press, Boston (2002).

[3] S. Mishra, S. Satpathy: Am. J. Phys. **69**, 512 (2001).
[4] J. B. Pendry and A. MacKinnon: Phys. Rev. Lett. **69**, 2772 (1992).
[5] E. Yablonovitch, T. J. Gmitter, and K. M. Leung: Phys. Rev. Lett. **67**, 2295 (1991).
[6] E. Ozbay, E. Michel, G. Tottel et al.: Opt. Lett. **19**, 1155 (1994).
[7] I. Tarhan, M. P. Zinkin, and G. H. Watson: Opt. Lett. **20**, 1571 (1995).
[8] T. Tanabe, M. Notomi, S.Mitsugi, A. Shinya, E. Kuramochi, Appl. Phys. Lett. **87(15)**, 151112 (2005).
[9] M.Popescu, J. Optoelectron. Adv. Mater. **3(2)**, 279 (2001).
[10] A.Bhargava. B.Suthar, Chalcogenide Lett. **6(10)**, 529 (2009).
[11] D. Freeman, C. Grillet, M.W. Lee, C.L.C. Smith, Y. Ruan, A. Rode, M. Krolikowska, S.T. Hanic, C.M. S.terke, M.J. Steel, B.L. Davies, S. Madden, D.J. Moss, Y.H. Lee and B.J. Eggleton, Photonics and Nanostructures: Fundamentals and Applications **6**, 3 (2008).
[12] A. Zakery, Y. Ruan, A.V. Rode, M. Samoc, B. Luther-Davies, J. Opt. Soc. Am. B **20**, 1844 (2003).
[15] K.M. Ho, C.T. Chan and C.M. Soukoulis, Phys. Rev. Lett. **65(25)**, 3152 (1990).
[16] B. Suthar, R. Khatri, A. Bhargava, Solid State Physics, India **54**, 381 (2009).
[17] B. Suthar, A. Bhargava, Int. J. of Pure and Appl. Phys. **6(1),** 31 (2010).
[18] J.S. Sanghera, C.M. Flora, L.M. Shaw, P. Pureza, V.Q. Nguyen, M. Bashkansky, Z. Dutton, J. D. Aggarwal, J. Non-Cryst. Solids **354**, 462 (2008).